magnetization hysteresis losses in the doped $Gd_5Ge_2Si_2$ compound are substantially reduced in comparison to the hysteresis losses of the undoped $Gd_5Ge_2Si_2$ compound. By adding a silicide-forming metal to the $Gd_5Ge_2Si_2$ compound in this manner, a magnetic refrigerant material highly suitable for near-room temperature applications is provided.

[0017] About one atomic percent of said silicide-forming metal can be added to the $Gd_5Ge_2Si_2$ compound in order to reduce hysteresis losses by more than 90 percent compared to the undoped $Gd_5Ge_2Si_2$ compound. Additionally, the resulting doped $Gd_5Ge_2Si_2$ compound exhibits significantly higher calculated effective refrigerant capacities than the $Gd_5Ge_2Si_2$ compound without silicide-forming metal additives.

[0018] The silicide-forming metal element can comprise at least one metal selected from a group of materials that includes one or more of the following: iron (Fe), cobalt (Co), manganese (Mn), copper (Cu), or gallium (Ga). When the silicide-forming metal element consists of Mn, Cu, or Ga, the hysteresis losses are reduced by nearly 100 percent, that is, the hysteresis losses are nearly eliminated.

[0019] In another aspect, the $Gd_5Ge_2Si_2$ compound alloyed with the silicide-forming metal additive is prepared by means of arc melting mixtures of the compound elements and silicide-forming metal element. The $Gd_5Ge_2Si_2$ compound alloyed with the silicide-forming metal additive is then heat treated to homogenize the compound.

[0020] In yet another aspect, there is provided a magnetic refrigerant alloy of the general formula: $Gd_5Ge_{1-X}Si_2M_X$, wherein M is a silicide-forming metal element and wherein x is an effective number selected such that hysteresis loss in the alloy is substantially smaller than when x=0.

[0021] X can be about 0.1. M can be at least one metal selected from the group consisting of Fe, Co, Mn, Cu, or Ga.

BRIEF DESCRIPTION OF THE DRAWINGS

[0022] The accompanying figures, in which like reference numerals refer to identical or functionally-similar elements throughout the separate views and which are incorporated in and form a part of the specification, further illustrate the present invention and, together with the detailed description of the invention, serve to explain the principles of the present invention.

[0023] FIG. **1**(*a*) depicts a backscattered SEM micrograph of a typical microstructure of the $Gd_5Ge_2Si_2$ alloy heat treated in a vacuum at 1300° C. for 1 hour;

[0024] FIGS. **1**(*b*) and **1**(*c*) depict backscattered SEM micrographs of the $Gd_5Ge_{0.9}Si_2Fe_{0.1}$ alloy heat treated in a vacuum at 1300° C. for 1 hour according to one embodiment;

[0025] FIGS. **2**(*a*) to (*d*) respectively depict backscattered SEM micrographs of the $Gd_5Ge_2Si_2$ compound doped with cobalt, copper, gallium, and manganese according to different embodiments;

[0026] FIG. **3** depicts a graph of magnetization versus field loops of the $Gd_5Ge_2Si_2$ compound heat treated in a vacuum at 1300° C. for 1 hour;

[0027] FIG. **4** depicts a graph of magnetization versus field loops of the $Gd_5Ge_{1.9}Si_2Fe_{0.1}$ alloy heat treated in a vacuum at 1300° C. for 1 hour;

[0028] FIGS. **5**(*a*)-**5**(*d*) depict graphs of magnetization versus field loops of the $Gd_5Ge_{1.9}Si_2Mn_{0.1}$, $Gd_5Ge_{1.9}Si_2Ga_{0.1}$, $Gd_5Ge_{1.9}Si_2Cu_{0.1}$ and $Gd_5Ge_{1.9}Si_2Co_{0.1}$ alloy samples heat treated in a vacuum at 1300° C. for 1 hour;

[0029] FIG. **6** depicts a graph of computed magnetic entropy change, ΔSm, versus temperature, integrated over applied field ΔH=3980 KA/m (5T), of the $Gd_5Ge_2Si_2$ compound heat treated in a vacuum at 1300° C. for 1 hour;

[0030] FIG. **7** depicts a graph of computed magnetic entropy change, ΔSm, versus temperature, integrated over applied field ΔH=3980 KA/m (5T), of the $Gd_5Ge_{1.9}Si_2Fe_{0.1}$ compound heat treated in a vacuum at 1300° C. for 1 hour,

[0031] FIG. **8** depicts computed magnetic entropy change, ΔSm, versus temperature of different $Gd_5Ge_{1.9}Si_2M_{0.1}$ alloys, wherein M=Co, Mn, Cu, or Ga, heat treated in a vacuum at 1300° C. for 1 hour; and

[0032] FIG. **9** depicts a table of computed Refrigeration Capacity (RC) and corresponding Effective Refrigeration Capacity (ERC) values for the compound $Gd_5Ge_2Si_2$ doped with different metal additives.

DETAILED DESCRIPTION OF THE INVENTION

[0033] The particular values and configurations discussed in these non-limiting examples can be varied and are cited merely to illustrate at least one embodiment and are not intended to limit the scope of the invention.

[0034] The method for reducing the hysteresis losses in the $Gd_5Ge_2Si_2$ refrigerant compound consists of alloying or doping the $Gd_5Ge_2Si_2$ compound with either a small amount of iron or other silicide-forming metal additive such as manganese, cobalt, copper, or gallium.

[0035] As will be described in more detail below, alloying the compound with a very small amount of the silicide-forming metal additive results in the reduction of the hysteresis losses by more than 90 percent and for some of the metal additives, the reduction is nearly 100 percent.

[0036] For the purpose of discussion hereinafter, the term "metal additive" refers to iron or other silicide-forming metal additive.

[0037] According to one embodiment, the $Gd_5Ge_2Si_2$ refrigerant compound doped or alloyed with iron was prepared by arc melting the appropriate elemental mixtures using a water-cooled copper hearth in an argon atmosphere under ambient pressure. The purity of the starting constituents was 99.9 wt. % and the chemical composition of the alloy resulting doped compound was $Gd_5Ge_{1.9}Si_2Fe_{0.1}$. Also, for the purpose of comparison, a $Gd_5Ge_2Si_2$ refrigerant compound was prepared by the same arc melting process, but without the metal additive. Prior to making magnetic measurements, using a SQUID magnetometer, each alloy was homogenized for one hour at 1300° C. in a vacuum.

[0038] Referring to FIG. **1**(*a*) of the accompanying drawings, which depicts a backscattered SEM micrograph of a typical microstructure of the heat treated $Gd_5Ge_2Si_2$ compound and FIGS. **1**(*b*) & **1**(*c*), which depict backscattered SEM micrographs of the heat treated $Gd_5Ge_{1.9}Si_2Fe_{0.1}$ alloy according to one embodiment, the micrographs show that the $Gd_5Ge_2Si_2$ compound **10** is single phase, whereas the $Gd_5Ge_{1.9}Si_2Fe_{0.1}$ alloy **11** is multiphase, with a dominant light gray phase surrounded by a darker minor intergranular phase.

[0039] FIGS. **3** and **4** respectively depict graphs of magnetization versus field loops **12** and **13** of the heat treated $Gd_5Ge_2Si_2$ compound **10** and of the heat treated $Gd_5Ge_{1.9}Si_2Fe_{0.1}$ compound **11**. The hysteresis loops showing the variation of magnetization, M, as a function of applied magnetic field, H, qualitatively illustrating the corresponding hysteresis losses of the compounds with and without the Fe metal additive in the 260-320 K temperature range. The magnetization versus field loops were obtained by isothermally mea-